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ABSTRACT. ***One of the important challenges in agricultural machinery research is the ability to effectively determine power requirements of a given field operation. The Controller Area Network (CAN) Bus, also known as ISOBUS, has proven to be an effective digital tool for tractor and implement data collection. This study attempted to determine implement hydraulic power requirements using a combination of existing public tractor CAN messages and minimal added sensors. The sensor signals were published on the CAN bus for ease of simultaneous sensor signal and CAN message data collection. Based upon the available CAN messages, this study attempted to measure hydraulic flow rate distributed by a tractor's directional control valve without the incorporation of a flowmeter. For instances when a valve received its requested flow rate by the operator, the valve's flow rate was predicted as a function of the valve's spool position. The resulting curve of best fit had a coefficient of determination of 0.9993 and a root-mean-square-error of 0.8805 Lmin^{-1} for the combination of multiple implement loads. When the valve became flow-limited, and the effective flow rate could no longer be determined by spool position, predicting the flow rate from a measured pressure drop across a minor loss in the system was investigated. From data collected on a flow-limited valve caused by reduced engine speed, a piece-wise line of best fit was found, predicting the flow rate based upon the pressure drop. Additional pressure sensors were used to determine the flow-state of the valve.***

Keywords. Agricultural Machinery, Controller Area Network Bus, Hydraulic Power, Implement Power, Tractor Power

Introduction

For decades, a significant area of agricultural machinery research has been to determine the true power requirements of implements used by tractors. The tractor is typically responsible for providing power to the implement in at least one of three forms: 1) drawbar power through the drawbar or three-point hitch to provide draft load to an implement, 2) rotational power through the power take-off (PTO), and 3) hydraulic power through the tractor's directional control valves. By having a firm understanding of power requirements expected for accomplishing desired tasks, producers can better select the correct tractor for their operation to reduce operation costs, fuel consumption, and emissions.

To conduct tractor performance data collection, for years, researchers have worked to equip tractors with additional sensors and a data acquisition system to measure variables needed to better understand the tractor's performance. Researchers have gone so far as to modify components of the tractor in order to fit their sensors and data acquisition systems on board (McLaughlin et al., 1993). However, after the incorporation of Controller Area Network (CAN) systems on tractors, not only did the technology provide simplified communication between electronic controller units (ECU) within the vehicle, but it also has served as a valuable data acquisition tool that researchers can use to better understand the tractor's performance (Darr, 2012). Certain CAN bus messages on the tractor follow the ISO 11783 universal standard which was built upon the SAE J1939 standard (Stone et al., 1999). Researchers can log these messages sent out on the bus through connection to the tractor's CAN diagnostic port, convert the known messages into engineering units, and analyze the values to understand tractor performance characteristics such as engine fuel rate requirements, field efficiencies, and engine load states (Al-Aani et al., 2016; Marx et al., 2016; Pitla et al., 2016; Pitla et al., 2014). In many cases, operational data published on the CAN bus may not be directly measured; thus, some amount of error may be expected (Marx et al., 2015). Limitations to data interpretation from the CAN bus often still exist when a desired variable is published in a proprietary format that cannot be interpreted, is recorded through an estimation but proven to be unreliable, or simply does not exist (Rohrer 2017). When this occurs, the incorporation of additional sensors have to be utilized to measure the desired missing variables, and then, if necessary, the data collected must be merged with the logged CAN messages (Lacour et al., 2014).

As technology and improved methods have advanced in recent years, there has been an increased demand for hydraulics in various implements. To measure hydraulic power requirements, from the equation listed in ASABE Standard EP496.3 (2011), entitled "Agricultural Machinery Management," pressure and flow rate of the hydraulic fluid must be known. Different implements require different numbers of hydraulic lines connected to the directional control valves (DCV), also commonly referred to as the remote control valves or selective control valves (SCV), of the tractor. To measure the true implement power requirements, each line's flow rate and pressure sent to and returned from the implement are required.

Ideally, for this study, a tractor would be selected that publishes the flow rate and extend and retract pressures of each DCV on the CAN Bus in the ISO 11783 standard message format. For example, for a DCV labeled number 1 where pressure and measured flow rate are needed, all of this data would be obtained from the message with the parameter group number (PGN) 65057 (FE21 in hex format). However, if this message is not available, if a particular valve's spool position is known, there still exists the potential to know the flow rate across the valve. Manring (2005) explains that the best way to model flow rate produced from a control valve is based upon the standard orifice equation. From this equation, an altered model is developed such that the flow rate of the valve can be inferred as a function of the pressure drop seen across the spool in the valve and the linear position of the spool which affects the discharge area and discharge coefficient of the orifice created by the spool (Manring, 2005). Thus, if the pressure drop can be measured across the spool valve, and the linear spool position of the valve is known, flow rate could be predicted without a flow meter. Moreover, in hydraulic systems that are pressure and flow compensated, between the load sense (LS) compensator on the main pump and a pressure compensator in the DCV, a constant pressure drop known as margin pressure is attempted to be maintained across the valve regardless of its spool position (Dell, 2017). Thus, with the model used to estimate flow rate of a valve, assuming a constant pressure drop, a direct relationship exists between the valve spool position and the flow rate sent to the implement by the valve. In order to test this relationship, the tractor must publish the spool position using the standard ISO 11783 message format for estimated flow determined by spool position. For a DCV labeled number 1, this data would be obtained from the message with the PGN 65041 (FE11 in hex format).

Even if it can be validated that flow rate can effectively be predicted by spool position in constant pressure drop situations within a valve, there still must be a way to accurately predict flow rate when the constant pressure drop no longer exists. Manring (2005) discusses that minor pressure losses in a hydraulic system can be determined by the flow rate of the system combined with the fluid density and a loss coefficient. All connection points between the tractor and implement hydraulics feature an ISO quick coupler where a minor loss occurs. If it is possible to accurately predict flow rate by deriving a loss coefficient and measuring the pressure drop across the coupler, it would serve as a far simpler solution than incorporating Manring's equation which takes into account both the pressure drop across the valve and the valve's spool position. Thus, for attempting to predict flow rate using the spool valve position, additional pressure sensors would have to be added.

If none of these messages are available or proven to be effective, then flowmeters will be required. Past studies have proposed different locations for the placement of the flow sensors. Lacour et al. (2014) added a flow turbine and transducer before the DCV stack in the line from the main pump. This method would measure the effective power delivered to the implement from the tractor; however, it would take into account a portion of the tractor's hydraulic system design instead of measuring solely the implement power requirements. Stoss et al. (2013) discussed how manufacturers are incorporating multiple pumps on tractors to use with implements that have a high flow and low pressure requirement in one line and a low flow and high pressure in another line. If this sensor location was used both on a tractor with a single pump and a tractor with multiple pumps, then for the same implement load conditions, the measured implement power requirements between the two tractors could be different. Thus, for this study, the flow sensor location should be within each line as opposed to just from the pump. Roeber et al., (2016) tested hose bend angles both upstream and downstream of a flowmeter to understand the acceptable orientations of a flow meter placed after a DCV stack. Despite Roeber et al. concluding any hydraulic bend angle is acceptable, with minimal room available on the tractor combined with a long upstream and downstream length requirements for flowmeter accuracy, the ability to eliminate the need for a flow meter would be preferred if possible.

The goal of this study was to enable the measurement of hydraulic implement power requirements utilizing the least number of modifications to an existing tractor. The specific objectives were to 1) develop a novel data acquisition system to acquire external sensor data and publish it to the CAN bus to better synchronize datasets, and 2) accurately predict flow rate and pressure delivered to the implement using only the CAN valve's spool position message combined with a minimal complement of additional pressure sensors. A series of tests were designed and implemented to prove system characteristics and evaluate the accuracy of flow prediction equations.

Materials & Methods

A John Deere 6145R tractor (Deere & Company, Moline, Ill.) was selected for use in this study. To collect CAN messages from the tractor, a CAN bus-to-USB interface (Danfoss CG-150, Danfoss North America, Ames, Iowa) was connected to the tractor's CAN diagnostic port, and messages were recorded into the proprietary software (Danfoss PLUS+1 GUIDE CANKing, Danfoss North America). Upon initial analysis of the PGN's published on the CAN Bus, it was determined the tractor did not publish flow rate, extend, and retract pressures in the standard ISO 11783 message format, but it did publish messages following the ISO 11783 format on estimated flow rate percentage based on valve spool position, engine speed, and hydraulic fluid temperature, all of which would be useful in testing. It was also determined that all of these messages were available on the implement bus of the tractor. Thus, the data logger did not additionally log data from the tractor bus. Various filters were incorporated into the CANKing software in order to only record desired messages from the implement bus.

For any additional sensors required for this study, it was determined that it would be ideal to publish data on the existing CAN Bus instead of using a separate data acquisition system for ease of data collection. The greatest advantage seen with this method was the elimination of synchronizing the separate sensor dataset together with the collected CAN messages. An electronics box was developed to house an additional electronic controller unit (ECU) (Danfoss MC-024-110, The Danfoss Group) that would publish added sensor data to the bus. This ECU was selected due to the simplified graphical programming software used to program the unit. The selected ECU featured pins that allowed for reading a variety of digital or analog inputs while also providing the ability to publish the sensor data on the CAN bus. Terminal blocks were added to the box to allow interchangeable connections for a variety of sensors. These terminal blocks provided necessary input voltage to the sensors and connected the output signals to the ECU. The box featured both an implement-end ISO breakaway connector that plugged into the tractor implement bus and a tractor-end ISO breakaway connector allowing an implement to plug into the bus as well when needed. A bracket was designed and built to fasten the box to the rear of the tractor to allow for mobile use. Figure 1 shows the ECU box and mount on the tractor under test.

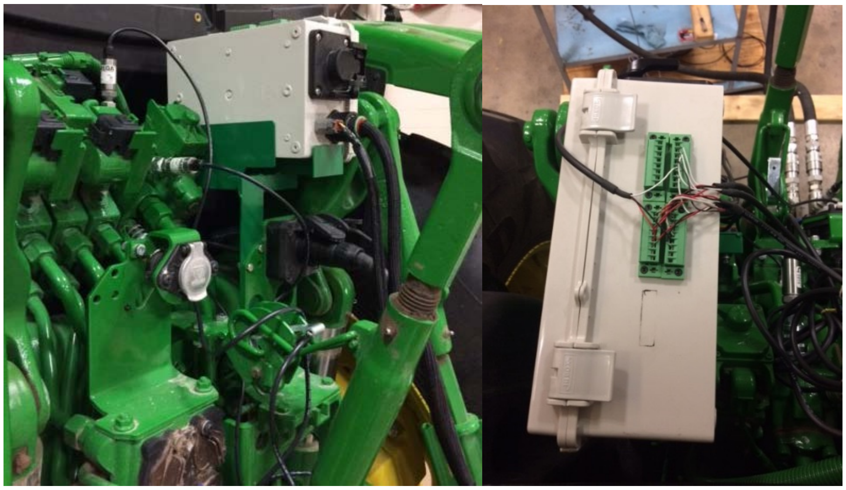

Figure 1: LEFT: ECU box and bracket mounted on rear of tractor under test. RIGHT: Top view of ECU Box. Terminal blocks located directly under rear window in cab allow for easier connection of sensors.

The pressure transducer (Omega PX309, Omega Engineering Inc., Norwalk, Conn.) selected for use in this study was chosen due to an input voltage range that could be provided by the CAN bus, a pressure rating of up to 34.48 MPa (5000 psi), and a linear relationship between pressure and the 0-5 V output signal. To determine whether a valve was in a flow-limited state, the pressure drop across each DCV main spool needed measured. To do this, pressure transducers were placed on the pump and LS test ports located on the rear of the tractor. When the difference in pressure between these signals became less than a nominal margin pressure setting, the system was flow-limited. Thus, at least one valve in the system would also not get its desired flow rate. To measure the pressure delivered to and returned from the implement, pressure transducers were placed immediately after the extend and retract ports. The pressure drop seen across the ISO coupler was inferred from the pressure difference between the LS and the higher of the extend or retract port pressures. Potential issues could result if the load check valve that is typically located within each DCV's extend and retract ports were to cause an additional pressure drop particularly at low flow rates (Dell, 2017).

To simulate the load created by an implement, a hydraulic loop circuit was constructed with an adjustable needle valve to allow controlled changes in the simulated implement load. A turbine flowmeter (Flo-tech Activa F6206-AVB-NN, Badger Meter, Milwaukee, Wisc.), the same flowmeter design used in the Roeber et al. (2016) study, was also incorporated into the circuit. The flowmeter data were published on the CAN bus through the added ECU to use as a baseline for determining relationships between flow rate and another measured quantity and understanding system characteristics. An analog pressure gauge was also added to the circuit to provide the operator an estimated implement load setting from the cab. The test hydraulic circuit used is shown in figure 2.

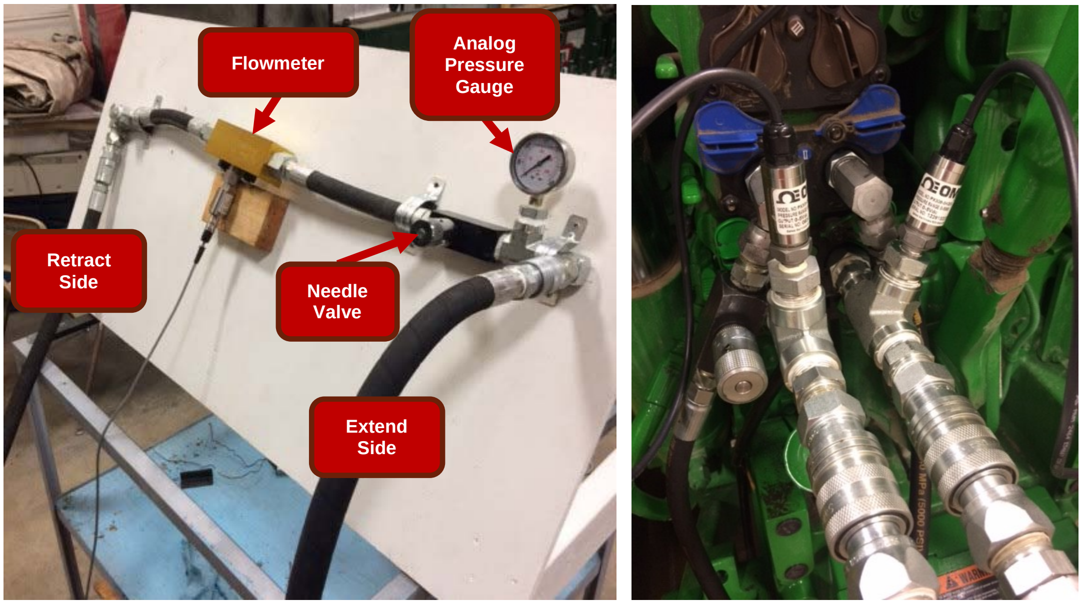

Figure 2: LEFT: Implement simulation circuit with needle valve and flow meter RIGHT: Implement pressure transducers located on extend and retract ports. Female ISO couplers allow for an implement to plug directly into the system.

For each test setup, three major inputs would be considered: 1) the needle valve setting representing implement load, 2) the speed of the engine, and 3) the spool position. In each test, two inputs would remain constant while the other would be modified after each trial. Thus, the three tests considered were 1) the effect of implement load on flow rate for a given valve position at rated engine speed, 2) the effect of engine speed on flow rate for a fully open valve at a given implement load, and 3) the effect of valve spool position on flow rate for a given load at rated engine speed. The DCV was placed into detent for each trial for a given period of time until enough data points were collected. From these tests, analysis of the relationship between flow rate and valve spool position in non-flow-limited valves and ISO coupler pressure drop and flow rate in flow-limited valves could be conducted.

Results & Discussion

A MATLAB program was created to post-process the data collected from the CAN bus. Steps in the data post-processing included sorting different messages by their PGN, converting raw data bytes into engineering units based upon the ISO 11783 standard, and resampling calculated engineering values from CAN messages to common time intervals. The resampled data could then be filtered to exclude data that were in transient states, and relationships could be analyzed through curves of best fit and shown visually through scatter plots.

The first variable considered was implement load requirement. A test with a constant desired flow setting around 70 percent was conducted at rated engine speed. After each trial, the needle valve was adjusted to produce a higher implement load. Figure 3 shows the implement pressure and corresponding flow rate recorded by the flowmeter over time. Seen from the figure, flow rate remains relatively constant for different implement load settings. However, at the highest two pressure settings in this study, around 17.5 and 18.0 MPA, the flow rate can no longer be maintained. This is due to the pump's pressure compensator beginning to destroke the pump. The pressure difference between pump and load sense stays constant at these higher pressures, but the pressure difference between LS and the implement drops. Thus, a high pump pressure combined with a lower than expected coupler pressure drop must be monitored to determine when a valve becomes flow-limited at high system pressures.

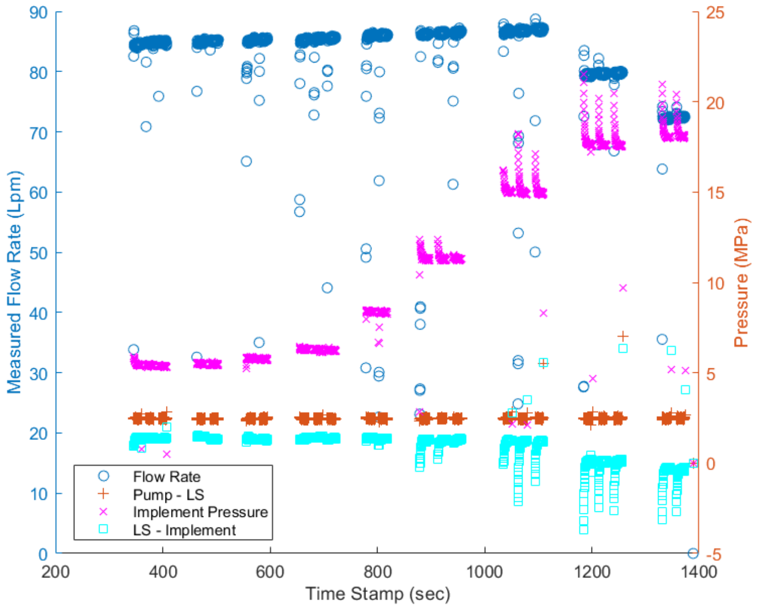

Figure 3: Flow rate and notable pressure drops versus time for a variable implement load trial.

The second variable considered was engine speed. For an implement load setting that would not result in a limited pump flow rate capability, and at a fully opened DCV spool setting, data was recorded at differing engine speed intervals of 100 rpm. Figure 4 below shows the resulting linear relationship observed between engine speed and the pump's flow rate output. Testing was repeated again but at a constant valve position setting around 50 percent. Figure 5 shows the results, where it is seen the valve flow rate is independent of engine speed except at lower engine speeds. When the valve is flow limited, the difference between pump and LS pressure decreases.

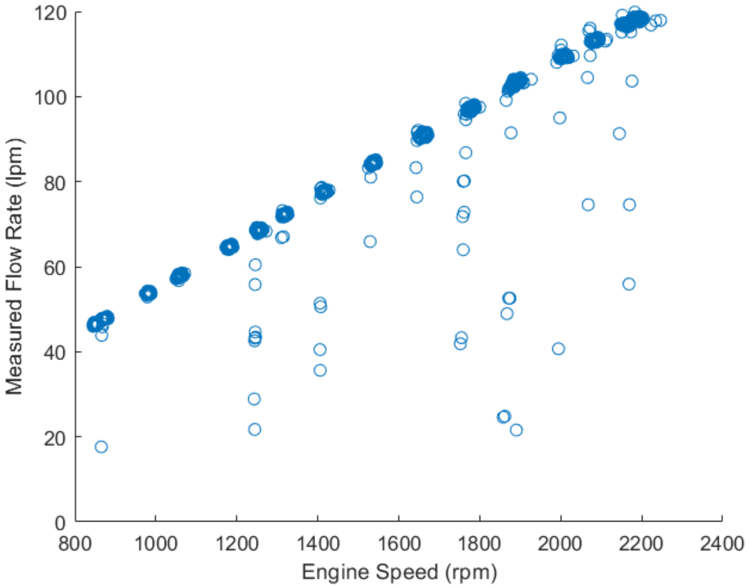

Figure 4: Measured flow rate versus engine speed test for a fully open spool

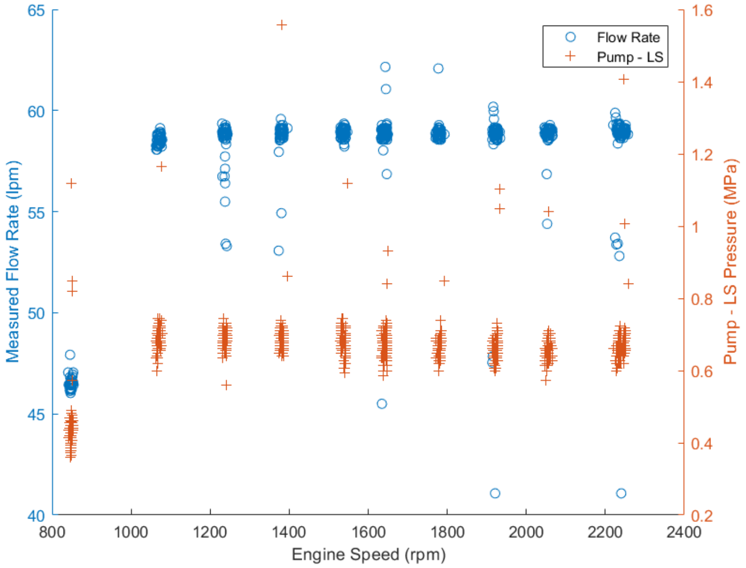

Figure 5: Measured flow rate and pressure difference between pump and LS with respect to engine speed for a 50% spool position.

After identifying high implement pressure and low engine speed as instances where a single DCV cannot maintain its desired flow rate, the third variable, spool position, was tested at rated engine speed and a pressure setting that would not result in a limited pump flow rate capability. Spool position was adjusted in roughly 5 percent intervals. As seen in figure 6, there was difficulty in being able to produce an estimated flow CAN message less than 30% and greater than 90% except when fully opened. The pressure difference between the pump and LS were used to indicate whether the valve ever became flow-limited. At the two highest spool positions recorded (86% and 100%), the pressure drop between the pump and LS decreased from nominal margin pressure, thus indicating the valve became flow limited at these settings. From viewing the figure, for non-flow-limited valve states, a direct relationship exists between valve spool position and flow rate.

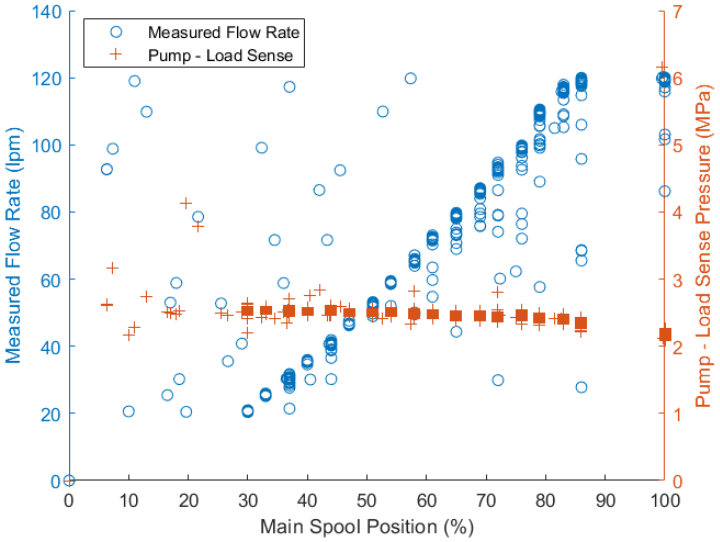

Figure 6: Relationship between flow rate and pressure differential between the pump and load sense for different valve spool positions

To further investigate this relationship, the data was again filtered to remove spool positions where less than 20 data points existed, thus signifying transient states that were not previously filtered, and flow-limited conditions at the highest spool positions. The mean flow rate of each remaining spool position was determined. A curve of best fit was determined based on the mean points. Figure 7 shows the mean flow rate for each spool setting with the curve of best fit. A root-mean-squared error (RMSE) of 0.7574 liters per minute (lpm) and a coefficient of determination (R^2) of 0.9993 resulted from the determined curve of best fit.

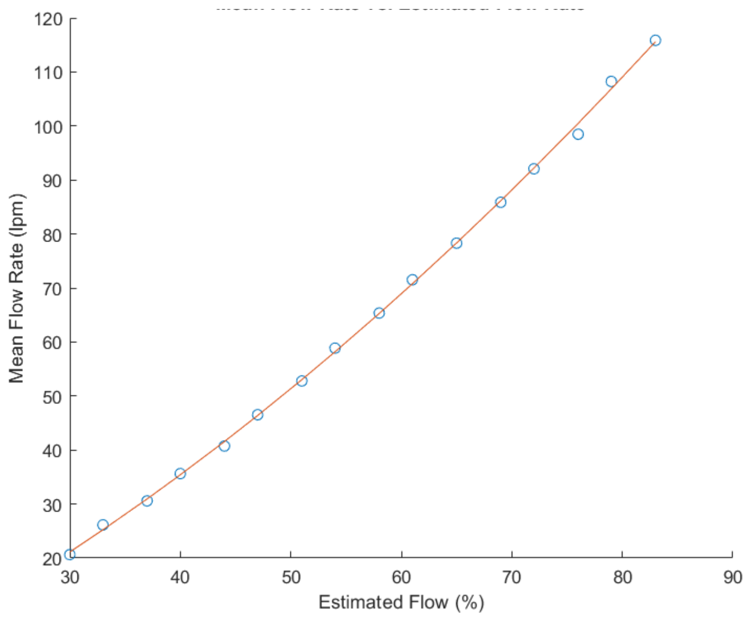

Figure 7: Mean flow rate per valve spool position with the determined curve of best fit.

From the variable implement load test, it was shown that flow rate remains constant for different implement loads at a valve spool setting. This assumes the implement load does not limit the pump's flow rate capability and the valve is not flow-limited by another condition. Thus, the expected curve of fit should closely match all implement loads that do not limit the pump. To prove this, a second test with variable spool positions was collected at a slightly higher load setting. A curve of best fit was computed taking into account both averaged datasets, and is shown below in figure 8. The curve resulted in a root-mean-squared error (RMSE) of 0.8805 liters per minute (lpm) and a coefficient of determination (R^2) of 0.9993 for the two datasets.

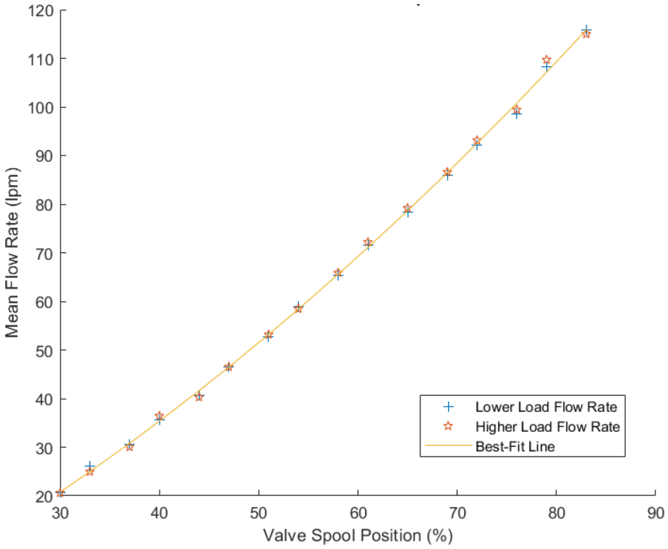

Figure 8: Mean flow rates versus spool position with curve of best fit for two load settings.

To analyze the relationship between pressure drop across a minor loss and flow rate for flow-limited valves, the variable engine speed test was used. When comparing the flow rates attained in the previously discussed variable engine speed test versus the variable spool position test, it was determined additional test points were needed at lower flow rates. As the pressure drop across a minor loss could be used to predict any flow rate, the incorporation of lower spool positions from the variable spool position test was combined with the variable engine speed test. Shown in figure 9, higher pressure drops occurred at the lowest flow rates of the dataset matching pressure drops seen at higher flow rates. As previously mentioned, this higher pressure drop likely could be attributed to the load check valves located in each DCV. Because two possible flow rates exist for certain pressure drops, a piecewise curve of best fit was used to predict flow rate. From the equation for minor pressures losses, figure 10 plots the flow rate as a function of the square root of the pressure drop seen for a given data point. Should the equation hold true, a linear relationship exists between the two variables. For higher flows, the resulting line of best fit had a RMSE of 2.946 liters per minute (lpm) and a R^2 value of 0.9878. For lower flows, the resulting line of best fit had a RMSE of 1.056 liters per minute (lpm) and a R^2 of 0.9099. However, if instead curves of fit are calculated, the higher flow rate curve achieved an RMSE of 2.480 lpm and R^2 of .9914, and the lower flow rates curve achieved an RMSE of .9011 lpm and a R^2 of .9314. Although there still exists two flow rates for certain measured pressure drops, the correct flow rate could likely be deciphered based on knowing the pump's maximum flow rate from calibration equations and other measured flow rates required of the implement.

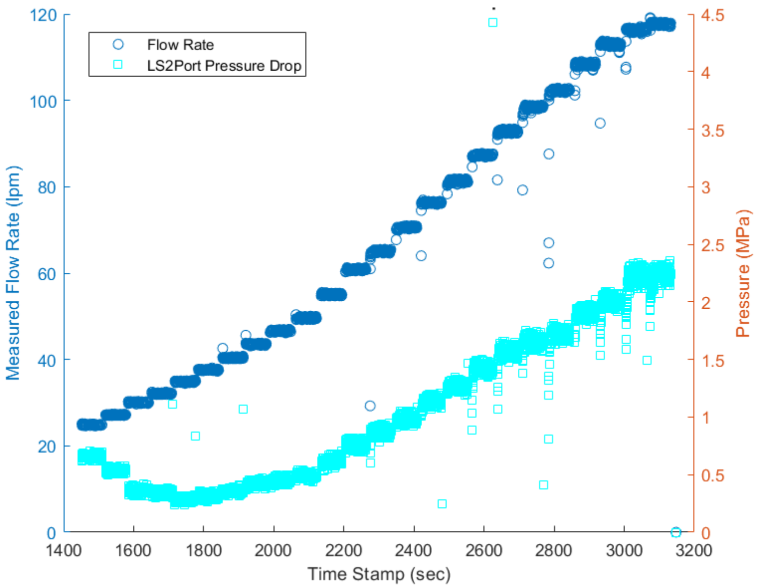

Figure 9: Plot of pressure drop across the ISO Coupler and corresponding measured flow rate over time

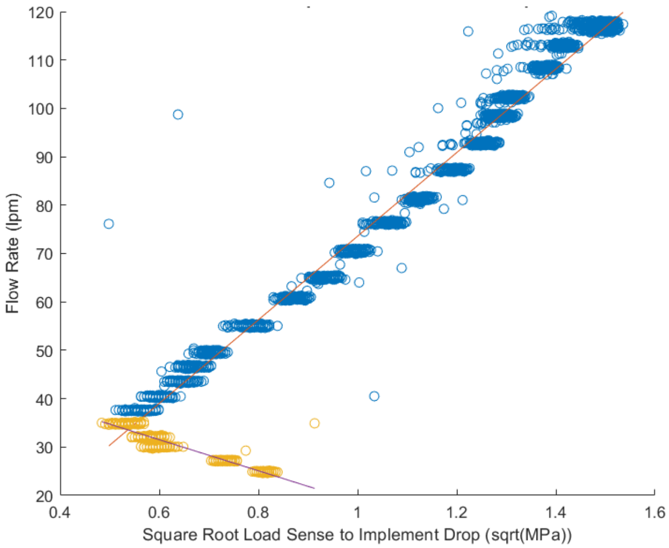

Figure 10: Data points and line of best fit for flow rate versus square root of measured pressure drop.

Conclusion

Given the design of most modern tractor hydraulic systems, including the tractor under test in this study, the actual flow rate sent through a valve to an implement can frequently be estimated solely by the valve's spool position. With the incorporation of the valve's spool position into the tractor's CAN bus system using a standard message format, the ability to measure this estimated flow rate input is simplified. This study was able to accurately form an equation relating spool position to flow rate for multiple load settings with a high coefficient of determination and low root-mean-square-error. However, as shown by the data collected in this study, scenarios exist when the valve spool position alone would incorrectly predict the true flow rate in the system. These scenarios include a lower engine speed, a higher working pressure requirement from the implement, and instances where multiple valves request a higher combined flow rate than the hydraulic pump's capability. When this occurs, a minor pressure loss seen in the ISO coupler connecting the implement to the tractor can be measured in an attempt to predict the flow rate through the valve. A more thorough investigation is needed to ensure a constant relationship between minor pressure drop and flow rate for each flow-limiting scenario. In particular, tests involving the use of multiple DCVs would be beneficial to better understand flow sharing between the valves and the effect on LS pressure. However, initial testing of flow-limited valves due to lower engine speed found a relatively strong relationship that can be modelled through a best-fit equation. Based on the calibration equations that could be determined for a valve, a program could eventually be developed that assigns a predicted flow rate to CAN message data collected. Thus, tests incorporating both flow-limiting and non-flow limiting valve states should also be developed with the incorporation of a flow sensor in the future to validate the program.

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